TITLE: Characteristics Analysis of SOI Waveguide Michelson Interferometers for Developing Biomedical Fiber Temperature Sensing Head

Characteristics Analysis of SOI Waveguide Michelson Interferometers for Developing Biomedical Fiber Temperature Sensing Head

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ABSTRACT

A new silicon-on-insulator (SOI) waveguide Michelson interferometer with Bragg reflective gratings as a biomedical temperature sensing array head is presented in this paper. The waveguide Bragg reflective gratings work as mirrors for adjusting the transfer function of the Michelson interferometer sensor. We will show the comparison of the temperature sensing accuracies of the fiber Bragg grating and SOI waveguide Michelson interferometers in biomedical applications. The grating length and perturbation period of waveguide Bragg grating in SOI waveguide Michelson interferometer will increase as temperature rises, that is, the thermal effects of the reflective Bragg gratings are considered in our analysis. According to the numerical analysis of power reflective spectra of waveguide Michelson interferometers, the temperature sensing of waveguide SOI Michelson interferometer can improve at least 20 times than traditional fiber Bragg grating temperature sensor. Moreover, the SOI waveguide interferometer sensor we designed presents high sensitivity than pure single waveguide Bragg grating sensor and fiber Bragg grating sensor by adjusting the length of the two interferomertric arms. The full width of half maximum (FWHM) of the frequency responses of passband of SOI waveguide Michelson interferometer can be designed smaller than fiber and waveguide Bragg grating sensors for sensitivity improvement.

Key words: Biomedical waveguide sensor, silicon-on-insulator, Michelson interferometer, waveguide, temperature sensor

1. INTRODUCTION

Because of the fiber Bragg gratings (FBGs) have many advantages such as high sensitivity, and biocompactibility provide excellent reliability for physiological temperature sensing, we have studied them for measuring temperature in the field of biomedical applications[1]. Fiber-optic temperature sensors have been widely studied[2-4]. Those fiber-optic sensors have many advantages, such as low volume and light weight, electromagnetic immunity and low cost. That is, to cooperate accurate fiber-optic temperature sensors with fiber-optic biomedical sensors is very desirable. Therefore, highly accurate

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fiber-optic temperature sensors are valuable in the trend of developing all fiber-optic physiological sensors. Moreover, some advanced fiber optical sensors using optical fiber interferometer structures have also been discussed and developed because of their high sensitivity in measurement of vibration, surface roughness, and chromatic dispersion, etc[5~9]. Recently, the integrated optical devices have shown outstanding performance as the tremendous promising developments of silicon-on-insulator (SOI) integrated electrical circuits[10~11]. Especially, the application of integrated optical periodic dielectric waveguide gratings in optical sensing have been widely studied[12~14].

In this paper, we designed a new SOI waveguide Michelson interferometer sensor for developing biomedical fiber temperature sensing head. The application scheme we proposed is shown in Fig. 1. The optical SOI waveguide Michelson interferometer sensor we designed are used for replacing fiber Michelson interferometer sensors for reducing the sensor size. This paper is organized as follows: Section 2 describe the mathematical formulations of our designed integrated optical waveguide Michelson interferometer sensor in temperature sensing. The numerical results of SOI waveguide Michelson interferometer sensor for temperature sensing are exhibited in Section 3. We also give the conclusions of our designed optical devices in final section.

2. MATHEMATICAL FORMULATIONS OF OPTICAL SOI WAVEGUIDE MICHELSON INTERFEROMETER SENSORS

In this section, we describe the mathematical formulations of the SOI optical waveguide Michelson interferometer sensors. The schematic structures of our designed SOI waveguide Michelcon interferometer and single SOI waveguide Bragg grating sensor on UNIBOND SOI wafer are shown in Fig. 2 and Fig. 3, respectively. The UNIBOND SOI wafer is designed with 1.5 μm thick silicon surface layers and 0.4 μm buried-oxide layer on silicon substrate. Considering the SOI waveguide coupler of Michelson interferometer sensor shown in Fig. 2, each arm has a length, l_i (i = *1 to 4*) and two SOI waveguide grating with reflection coefficient r is designed in the ends of two output arms. The light is launched at any arm and reflected and interfered in our designed Michelson interferometric cavity to achieve narrow optical passband spectra for increasing sensor sensitivity.

The scattering matrix method[15] is used for deriving the reflected optical fields from output ports of the SOI waveguide Michelson interferometer and are derived as following terms:

$$E_{r_1} = \frac{re^{-i\beta l_1}}{(1-K)}[Ke^{-2i\beta l_3} + (1-K)e^{-2i\beta l_4}]E_{in} \tag{1}$$

$$E_{r_2} = [\frac{i\sqrt{K}}{\frac{K}{\sqrt{1-K}} + \sqrt{1-K}} r(e^{-2i\beta l_3} + e^{-2i\beta l_4})e^{-i\beta(l_1+l_2)}]E_{in} \tag{2}$$

$$E_{r_3} = [i\sqrt{K}(1-r)^2 e^{-i\beta(l_1+l_4)}]E_{in} \tag{3}$$

$$E_{r_4} = [\sqrt{1-K}(1-r)e^{-i\beta(l_1+l_4)}]E_{in} \tag{4}$$

where E_{in} is the initial input optical field, K is the coupling constant of the SOI waveguide coupler, β is the propagating constant, $l_{i(i=1,2,3,4)}$ is the length of each arm, r is defined as the reflected power ratio of SOI waveguide Bragg grating with amorphous silicon cover and is derived in the following. In this paper, we will show the improvement of the accuracy with replacing the fiber Bragg gratings by SOI waveguide Michelson interferometer sensors. The author can determine the variance of temperature by designing and analyzing the reflecting power spectra of waveguide devices. A periodic sinusoidal index corrugation is distributed along the direction of this waveguide device. We may derive the reflected power of single SOI waveguide Bragg grating sensor with amorphous silicon cover based on the coupled-mode equations[16] as

$$r = \frac{\left(\frac{\pi\Delta nf}{c}\right)^2 \sinh^2\left[\sqrt{\left(\frac{\pi\Delta nf}{c}\right)^2 - \left(\frac{2\pi nf}{c} - \frac{\pi}{\Lambda}\right)^2}\, L\right]}{\sqrt{\left(\frac{\pi\Delta nf}{c}\right)^2 - \left(\frac{2\pi nf}{c} - \frac{\pi}{\Lambda}\right)^2}^{\,2} \cosh^2\left[\sqrt{\left(\frac{\pi\Delta nf}{c}\right)^2 - \left(\frac{2\pi nf}{c} - \frac{\pi}{\Lambda}\right)^2}\, L\right] + \left(\frac{2\pi nf}{c} - \frac{\pi}{\Lambda}\right)^2 \sinh^2\left[\sqrt{\left(\frac{\pi\Delta nf}{c}\right)^2 - \left(\frac{2\pi nf}{c} - \frac{\pi}{\Lambda}\right)^2}\, L\right]} \tag{5}$$

where L is the length of Bragg grating, Δn is the grating index perturbation, c is the light speed in free space, f is the optical frequency, n is the refractive index and Λ is the period of the waveguide Bragg grating. From Eq. (5), we know that the maximum power reflection only occurs on the phase matching condition. When we considered the variance of temperature ΔT of SOI wafer under monitoring biomedical signals, the central optical frequency of the reflecting spectrum will drift as f_R as[17]

$$f_R = \frac{c}{[1+(E+T_0)\Delta T]2n\Lambda} \tag{6}$$

where E and T_0 are the thermal expansion coefficient and the thermo-optic coefficient of the SOI waveguide Bragg grating, respectively. The parameters for analyzing the reflective spectra of SOI waveguide sensor and fiber sensor are listed in Table I[18]. The length L and period Λ of waveguide Bragg grating will increase as temperature rises, that is, the thermal effects are considered in our analysis.

3. NUMERICAL RESULTS OF SOI WAVEGUIDE MICHELSON INTERFEROMETER SENSORS FOR TEMPERATURE SENSING

Through a serial analysis and derivations of the work formulations mentioned above, Fig. 4 shows the numerical results of the reflected spectra of FBG and SOI Michelson interferometer sensor with the temperature variation 10℃. The numerical results of the reflected spectra of SOI waveguide grating sensor and SOI Michelson interferometer sensor with the temperature variation 10℃ is shown in Fig. 5. The SOI Michelson interferometer sensor is designed with K= 0.5, $l_1 = l_2$ =3 mm, l_3 = 4 mm, l_4 = 4.068 mm, L = 0.1 mm, and Λ=0.2215 μm. The SOI grating sensor with L=0.1 mm and Λ =0.2215 μm, the same parameters for comparing with SOI Michelson interferometer sensor. The fiber Bragg grating sensor is designed with L=5mm and Λ=0.5166 μm for achieving the same reflected spectrum as SOI grating sensor. In Fig. 4 and Fig. 5, the FBG sensors and SOI waveguide Bragg grating sensors were compared with SOI waveguide Michelson

interferometer sensors, assume all of the devices have the same initial center wavelength of the reflection spectrum at 1.55 μm. Especially, the FBG sensor and SOI grating sensor are designed with almost the same reflection spectra at initial setting temperature as a solid line in Fig. 4 and Fig. 5 with the 10℃ temperature variation, the reflecting spectra shifting show the SOI grating has much better response. Attaching the same SOI waveguide grating on the ends of a 2 x 2 optimal SOI coupler, the reflecting spectra coming from the output port 2 of the designed SOI Michelson interferometer sensor show a narrow bandwidth. Therefore, a SOI waveguide Michelson interferometer sensor has higher sensing resolution for biomedical applications.

4. CONCLUSION

According to the numerical analysis of the power reflective spectra of waveguide Michelson interferometers mentioned above, the temperature sensing of waveguide SOI Michelson interferometer for developing biomedical fiber temperature sensing head can improve at least 20 times than fiber Bragg grating temperature sensor. Moreover, the SOI waveguide interferometer sensor we designed presents high sensitivity than pure single waveguide Bragg grating sensor. The full width at half maximum (FWHM) of the frequency responses of passband of SOI waveguide Michelson interferometer can be designed smaller than fiber Bragg grating sensors for sensitivity improvement. Owing to excellent characteristics of smaller FWHM and high finesse in temperature sensing for biomedical signal monitoring, the waveguide SOI Michelson interferometer we designed may replace the traditional fiber Bragg grating sensors system for biomedical applications.

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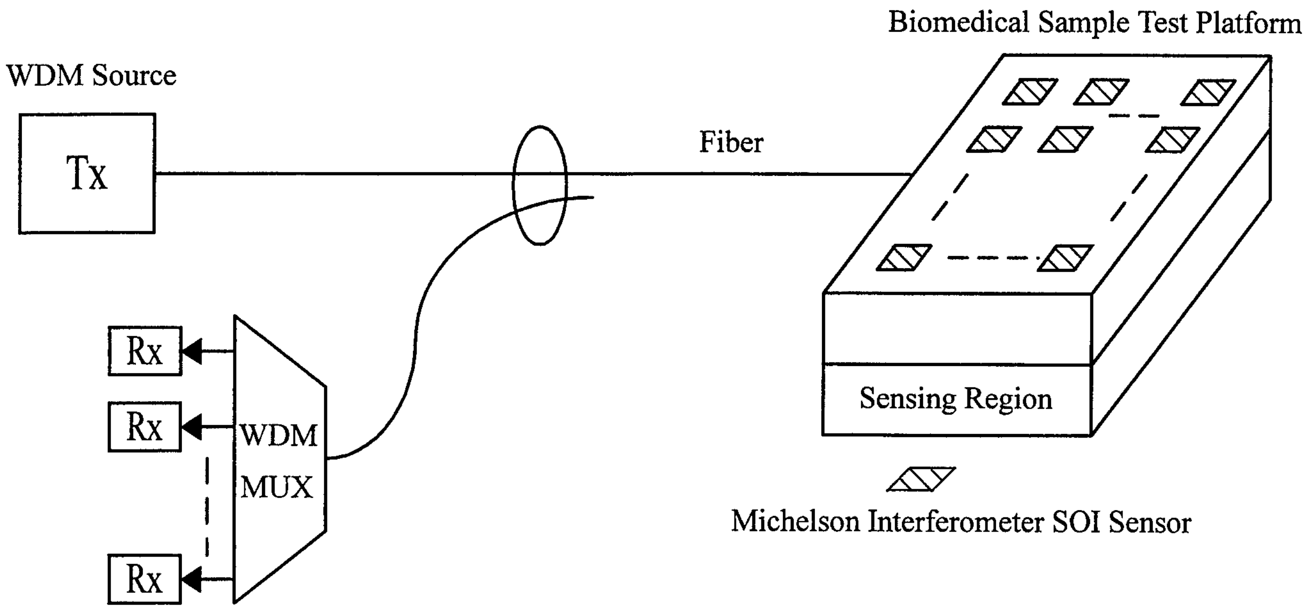

Fig. 1 The design of a SOI waveguide Michelson interferometer for developing biomedical fiber temperature sensing head

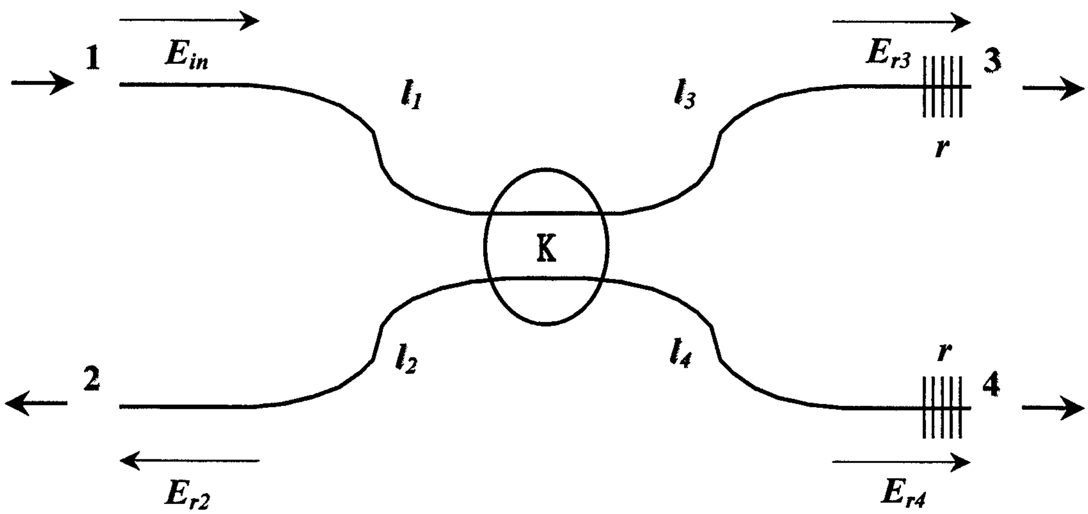

Fig. 2 The schematic diagram of a SOI waveguide Michelson interferometer sensor

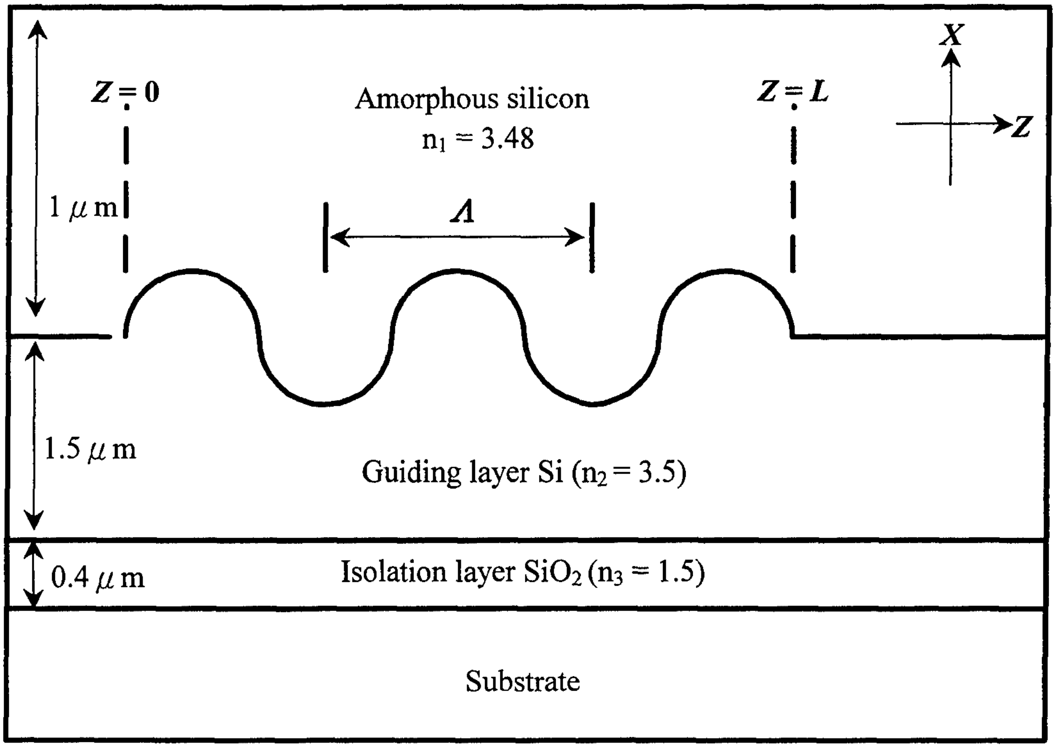

Fig. 3 The schematic diagram of a sinusoidal-index SOI Bragg grating waveguide with amorplous silicon cover sensor

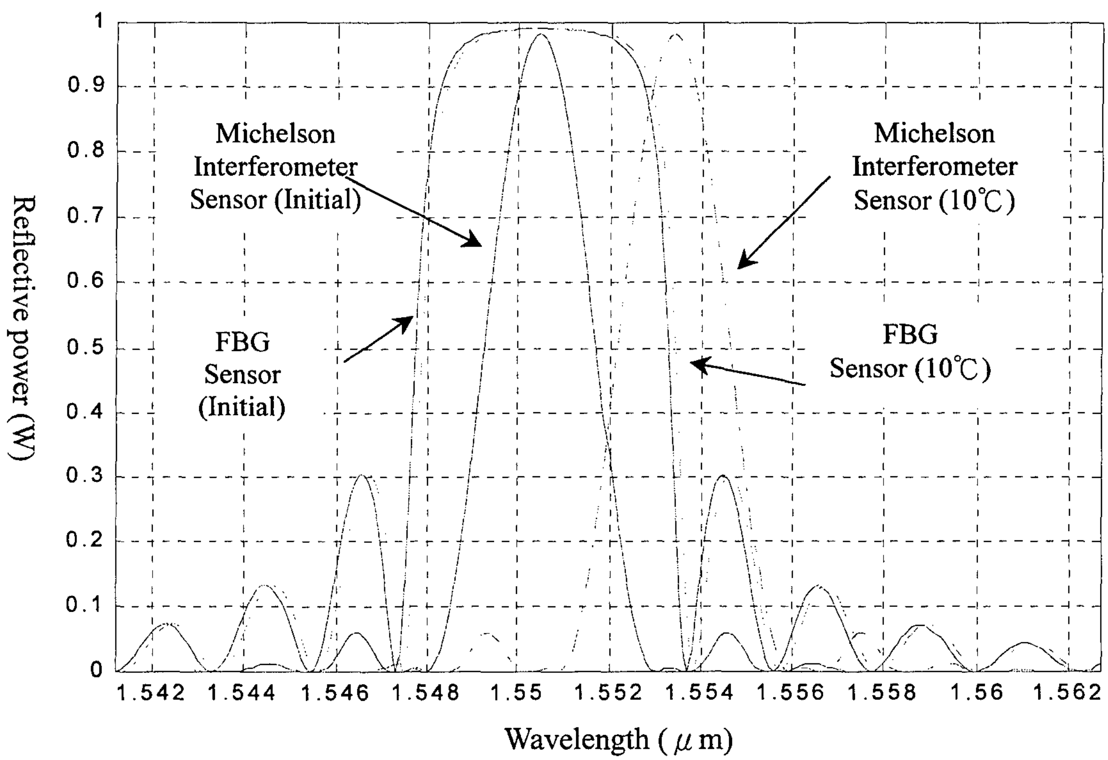

Fig. 4 The comparison of the reflected spectra from FBG and SOI Michelson interferometer sensor with temperature 10℃ offset from the initial temperature

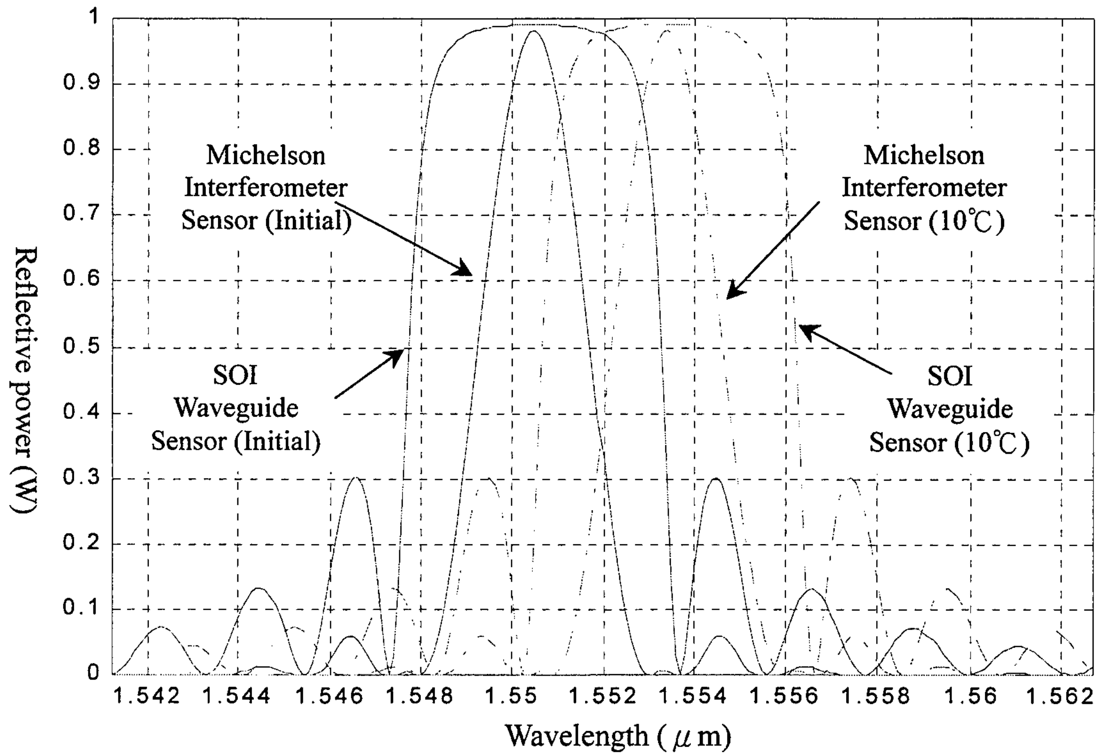

Fig. 5 The comparison of the reflected spectra from SOI waveguide grating sensor and SOI Michelson interferometer sensor with temperature 10℃ offset from the initial temperature

Parameters	**Thermal Expansion coef. (E)**	**Thermal-Optical coef. (T_0)**
SOI Wavaeguide Grating	**2.6×10^{-6}/℃**	**1.86×10^{-4}/℃**
Fiber Bragg Grating	**1.1×10^{-6}/℃**	**8.6×10^{-6}/℃**

Table I Some thermo-optical parameters of fiber Bragg grating and SOI waveguide Bragg grating used in this study